PHYSICAL REVIEW A VOLUME 28, NUMBER 6 DECEMBER 1983

Triple-differential probabilities for the emission of δ electrons in 10-MeV F^{q+}+Ne ($q=6$, 8, 9)

A. Skutlartz and S. Hagmann
Department of Physics, Kansas State University, Manhattan, Kansas 66506
(Received 12 May 1983)

Absolute triple-differential probabilities for the emission of δ electrons in the near-symmetric collision system 10-MeV F^{q+}+Ne, for $q=6$, 8, and 9, have been measured as a function of the impact parameter, the δ-electron energy, and the δ-electron emission angle. The impact-parameter dependence of these probabilities features for all observed collision systems, electron energies, and emission angles a sharp rise to a constant maximum at about 1.5 times the neon K-shell radius r_K and fall off for impact parameters $b>r_K$ somewhat exponentially with increasing electron energy. For an electron emission at 52.5° with respect to the beam axis this energy dependence is distorted by the occurrence of a binary-encounter peak. The δ-electron emission probabilities show a strong asymmetry for electrons emitted in forward beam direction. A comparison of the experimental data obtained in 10-MeV F^{9+}+Ne at an electron emission angle of 90° with a recent semiclassical-approximation-type calculation shows discrepancies in both the impact-parameter dependence and in magnitude of the emission probabilities. However, the energy dependence is reproduced reasonably well in this model.

I. INTRODUCTION

During the last decade a large number of experiments have been undertaken to investigate the emission of δ electrons, i.e., electrons ejected in the primary collision process in ion-atom collisions.[1–13] These electrons, emitted from a specific atomic state, often provide a more direct insight into the collision mechanisms and atomic structures involved than the observation of secondary decay products (photons, Auger electrons) from the ionized target.

A mechanism responsible for the production of δ electrons is the direct Coulomb ionization. When a charged particle (ion) passes through or near an atom, the most prominent interaction is the Coulomb attraction between the ion and the orbital electrons of the target. This interaction causes the electrons to be "pulled out" of the atom, provided the energy given to it is enough to raise it from its binding in the potential well of the target nucleus to the continuum. Since the Coulomb interaction is well understood, these experiments provide useful information for comparison with various theoretical models. However, since mostly total, singly, and doubly differential cross sections as a function of δ-electron energy and emission angle for proton impact[1–7,10,12,13] and for a few heavier projectiles[8,9,11] in gaseous targets have been obtained, only information on the final result of such an ionization process can be extracted; knowledge about the dynamics of the ionization process itself cannot be easily deduced.

Only recently results became available that have been obtained by applying stricter conditions on the experimental collision system. Weiter and Schuch[10] reported on the energy distribution of δ electrons from the argon K shell following proton impact, and Cocke *et al.*[11] for the first time measured the impact parameter dependence of δ electrons in S^{q+} + Ar, $q=5$ and 11, collisions. While both experiments require the use of coincidence techniques, the latter is of special interest, since fixing the impact parameter allows one to determine the momentum carried into the collision by the projectile and thus provides an important piece of information about the kinematics of the ionization process itself. Cocke *et al.* found an increase of the δ-electron emission probability with increasing impact parameter, but did not measure far enough to observe a maximum. A comparison of their results with theoretical models proved difficult, since the influence of electrons carried into the collision by the projectile on the probability is not well determined.

In the light of this situation, we chose to investigate the δ-electron emission probability more thoroughly. Collisions of 10-MeV fluorine ions with a gaseous neon target have been chosen as the subject of the experiment, since various aspects of this system have been studied over the last years by several groups at Kansas State University.[14–17] Therefore previous results are readily available, and the experimental procedure is well understood. Our goal was to obtain triple-differential probabilities for the emission of δ electrons from collisions of lithiumlike, hydrogenlike, and bare fluorine ions with neon as a function of the impact parameter, the δ-electron energy and the δ-electron emission angle.

II. EXPERIMENTAL PROCEDURE

A. Technique

A beam of fluorine ions of charge state $q=3+$ from the Kansas State EN Tandem Van de Graaff was accelerated to an energy of 10 MeV. After poststripping in 10-μg/cm^2 C foils the beam was magnetically charge-state

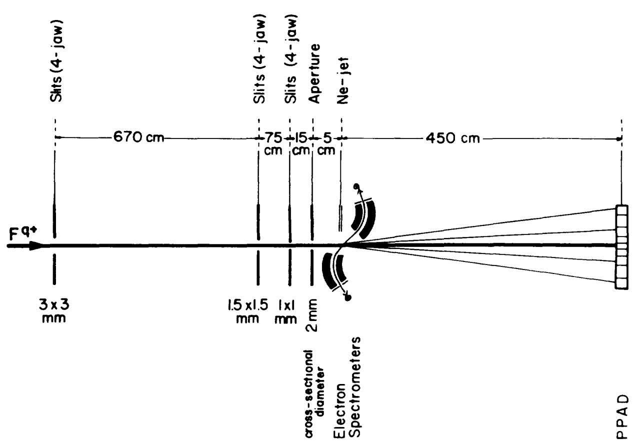

FIG. 1. Experimental set up to measure coincidences between scattered fluorine projectiles and neon δ electrons. The spherical sector electron analyzers can be rotated to detect electrons emitted at 52.5°, 90° or 127.5° with respect to the beam axis. Scattered particles are registered in a position-sensitive parallel-plate avalanche detector (PPAD).

selected to $q=6+$, $8+$, or $9+$. On the way to the target gas region the beam was passed through two magnetic quadrupoles and a magnetic deflector and was, over a length of 750 cm, tightly collimated by three adjustable slit systems (typically open to 3×3 mm^2, 1.5×1.5 mm^2, and 1×1 mm^2), the last one serving as a beam scraper to reduce slit scattering, and passed through an aperture of 2 mm diameter, which was the only connection between the beam line and the scattering chamber (see Fig. 1). The neon gas was brought into the separately pumped interaction region through a hypodermic needle ($d=0.5$ mm). The pressure in the beam line during experiments was better than 5×10^{-7} Torr. The pressure in the interaction region was always kept low enough that charge-changing collisions played no role and was estimated[15] to be 150 to 200 mTorr in the target region over a beam length of 3 to 4 mm.

Scattered projectiles were detected by a 16-annulus position-sensitive parallel-plate avalanche detector (PPAD), which has been described elsewhere.[18] This detector has a ring geometry allowing one to detect simultaneously scattered particles over an impact-parameter range $b_{\max}\simeq10b_{\min}$ with a resolution $\Delta b/b\simeq5\%$. It has been used to register scattered projectiles which have been deflected between 3.5 and 42 mm over a flight path of 450 cm, thus detecting scattering events for the system 10 MeV $F^{q+}+Ne$ with impact parameters between 0.05 and 0.45 a.u. Since only the angle into which the projectile is scattered, not the impact-parameter b, is experimentally accessible, and calculations give probabilities as a function of the impact parameter, a relation between these two quantities has to be established. For a pure Coulomb internuclear potential, one obtains the well-known relationship

$$b=\frac{Z_P Z_T}{2E^{\mathrm{c.m.}}\tan(\frac{1}{2}\theta^{\mathrm{c.m.}})}$$

where $\theta^{\mathrm{c.m.}}$ is the center-of-mass scattering angle and $E^{\mathrm{c.m.}}$ is the center-of-mass energy. In the present collision system, the validity of pure Rutherford scattering for small scattering angles cannot be assumed due to the screening of the target electrons. An exponentially screened potential of the form

$$V=V_{\mathrm{Ruth}}\exp(-r/a)$$

has to be applied to the problem, using a screening parameter $a=0.52$ a.u. deduced from an experimentally obtained scattering function.[15]

Electrons emitted at an average angle of 52.5°, 90°, and 127.5° with respect to the beam direction were energy analyzed with two identical electrostatic spherical sector analyzers located opposite to each other on both sides of the ion beam. Electrons were registered by channel electron multipliers. The electron energy resolution of the analyzers was chosen to be $\approx2.5\%$ and the effective solid angle subtended by each spectrometer was 5×10^{-2} sr. Both spectrometers could be moved on their support beams perpendicular to the ion beam axis without breaking the vacuum, thus ensuring that the focusing points coincide in one single point in the intersection of the ion beam and the gas jet and thus define a unique source volume for both analyzers. The target region and the spectrometers were confined in a closed μ-metal cylinder with apertures for the beam, the gas jet and pumping holes to assure the compensation of stray magnetic fields.

Electrons were detected in coincidence with scattered projectiles using a standard fast-slow coincidence technique. The electron energy was scanned simultaneously with both electron spectrometers over a range of 200 to 1500 eV with a low repetition rate ($<10^{-2}$ Hz). Data were stored as electron spectra, scattered-particle spectra, and coincidence [time-amplitude conversion (TAC)] spectra in pulse-height analysis on floppy disks and in a time-correlated three-parameter list mode on magnetic tape.

Before and after every data-taking run, and after every change of focusing of the beam or other beam properties, the amount of slit scattering was determined. Contributions from slit scattering to the total number of scattered projectiles were typically 10 to 15 % for scattering angles smaller than 4×10^{-3} rad, for larger scattering angles they amounted to 30 to 50 %. All data presented here were corrected for these contributions.

B. Data evaluation

The following collision systems have been investigated to determine the δ-electron emission probabilities as a function of the impact parameter b, the δ-electron energy E_δ, and the δ-electron emission angle Φ:

10-MeV $F^{6+}+Ne$, $\Phi=90°$,

10-MeV $F^{8+}+Ne$, $\Phi=90°$,

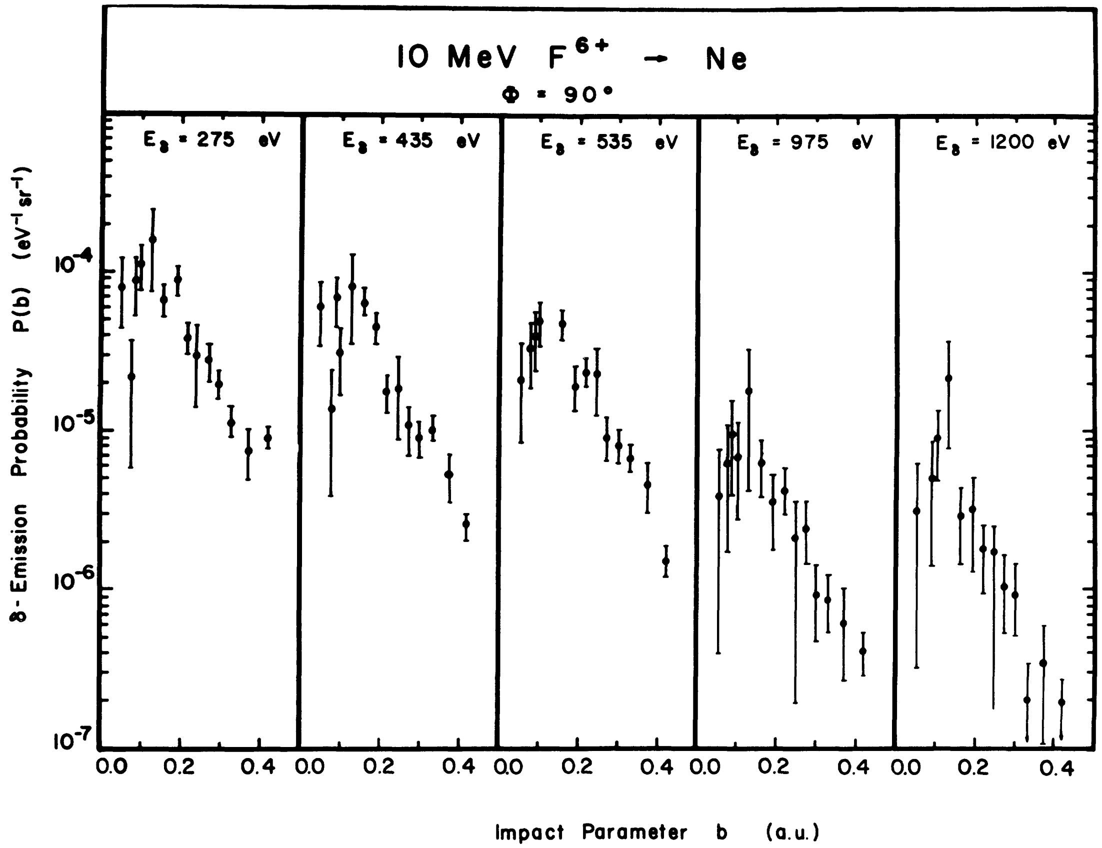

FIG. 2. Impact-parameter dependence for the neon δ-electron emission probabilities at $\Phi=90°\pm21°$ for lithiumlike fluorine projectiles at 10 MeV. The impact parameter is subject to an uncertainty of ±5%, the δ-electron energy is uncertain within ±40 eV.

and

$$10\text{-MeV } F^{9+}+\text{Ne},\ \Phi=52.5°,\ 90°,\ \text{and } 127.5° .$$

The data stored on magnetic tape were sorted into windows of the TAC spectrum and projected on regions of the scattered-particles spectrum, yielding, after the subtraction of random coincidence events, spectra of δ-electrons truly coincident with scattered projectiles as a function of the scattering angle.

Since the position and energy of the neon K-Auger hypersatellite and satellite lines are known,[14–17] the coincident electron spectra can be energy calibrated. Windows of 80 eV width are chosen around δ-electron energies E_δ, and the number of δ electrons $N_\delta(b,E_\delta,\Phi)$ within these windows are determined and normalized to a window width of 1 eV.

The probability for the emission of δ electrons per collision event is given by

$$P(b,E_\delta,\Phi)=\frac{N_\delta(b,E_\delta,\Phi)}{N_p(b)}\frac{1}{\epsilon_e}\frac{1}{d\Omega_e} ,$$

where $N_p(b)$ is the number of off-the-target gas scattered projectiles detected at a scattering angle θ, and ϵ_e and $d\Omega_e$ are the efficiency and solid angle of the electron spectrometers. The efficiency ϵ_e was not determined directly, but since the absolute probabilities as functions of the impact parameter for the production of the neon K-Auger satellite and hypersatellite electrons are known,[15–17] the data in the experiment presented here could be normalized to these known probabilities via

$$P(b,E_\delta,\Phi)=\frac{N_\delta(b,E_\delta,\Phi)}{N_K(b)}P_K(b)\frac{E_0}{E_\delta}\alpha$$

(1/eV sr), where $N_K(b)$ is the observed number of coincident Auger electrons, $P_K(b)$ is the corresponding absolute probability for the production of K-Auger electrons, E_0/E_δ is a correction factor to compensate the constant $\Delta E/E$ of the electron spectrometers, and α is a normalization constant correcting the probabilities for the finite size of the solid angle of the electron spectrometers and the width of the window in electron energy chosen to determine $N_\delta(b,E_\delta,\Phi)$ $(\alpha=d\Omega_e/80=5\times10^{-2}/80=6.25\times10^{-4})$.

To obtain $N_K(b)$ from the sorted and projected coincident electron spectra, several methods had to be applied. In the collision system F^{9+} + Ne, $\Phi=90°$ and 127.5°, the number of δ electrons underlie the peaks of K-Auger electrons in the coincident electron spectra is almost negligible compared to the number of Auger electrons. Thus $N_K(b)$

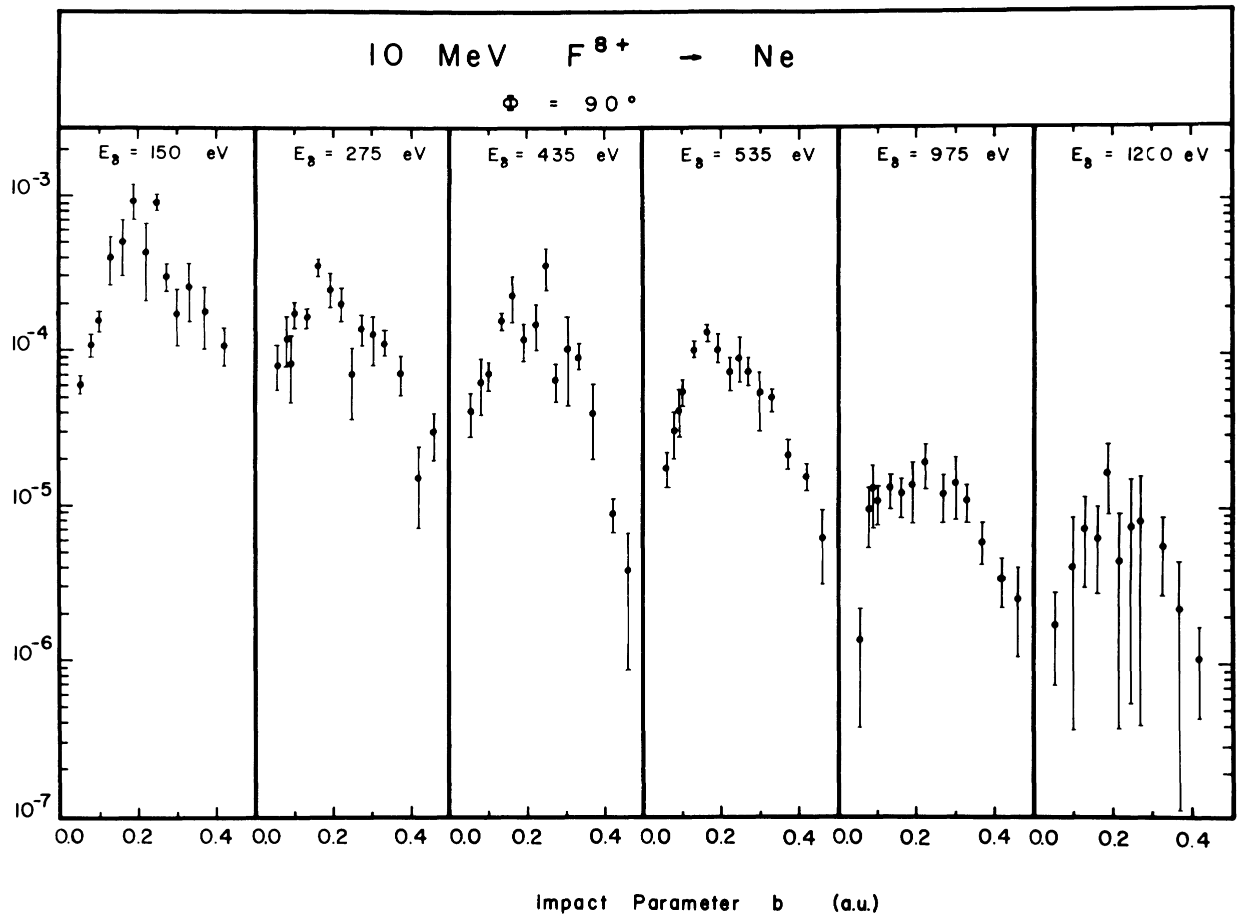

FIG. 3. Same as in Fig. 2, but for hydrogenlike fluorine projectiles.

could be obtained directly from these spectra. In the case of F^{6+} and F^{8+} impinging on neon, the δ electrons under the K-Auger peaks contribute less than 20 and 10%, respectively, to the Auger electrons. This contribution is well within the statistical error of the count rate and thus no elaborate procedure was necessary to correct for these effects. However, in the case of electron emission at beam forward angles, i.e., F^{9+} + Ne, $\Phi=52.5°$, a distinct contribution of δ electrons underlie the K-Auger peaks. To compensate for these electrons, a fit program written by M. Stöckli[19] was used to obtain $N_K(b)$.

$P_K(b)$ was obtained from a smooth-curve fit to the experimental data points for the K-K charge transfer[15–17] and the values corresponding to this curve were used.

This normalization did yield a constant efficiency $\epsilon_e \simeq 10\%$ of the electron spectrometers over the whole range of electron energies covered. As a control measure, the obtained $N_K(b)$ were divided by $N_p(b)$. The relative probabilities thus obtained for K-Auger electron emission reproduce the shape of the K-K transfer probabilities within statistical errors.

During the data-evaluation process the δ-electron energies become subject to an uncertainty of ±40 eV. Completely within this margin lies an uncertainty due to the Doppler shift of the electron energy.[20] Owing to the construction of the spherical sector spectrometers, the angles at which the electrons can be detected cover a range of $90°\pm21°$, $127.5°\pm7.5°$, and $52.5°\pm7.5°$ with respect to the beam direction. The uncertainty in the δ-electron emission probabilities is given for each data point in Figs. 2—6. Three main features contribute to this uncertainty, the statistical error in $N_\delta(b,E_\delta,\Phi)$, the statistical error in $N_K(b)$, and the uncertainty of $P_K(b)$.[15–17]

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Results

The obtained triple-differential probabilities $P(b,E_\delta,\Phi)$ for the emission of δ electrons can be presented in three ways:

(a) As a function of the impact-parameter b, indicating the internuclear distance at which the emission of δ-electrons is most likely;

(b) as a function of the δ-electron energy E_δ, yielding the energy distribution of δ electrons;

(c) as a function of the δ-electron emission angle Φ, providing information about the angular dependence of the δ-electron emission.

(a) δ-electron emission probabilities as functions of the

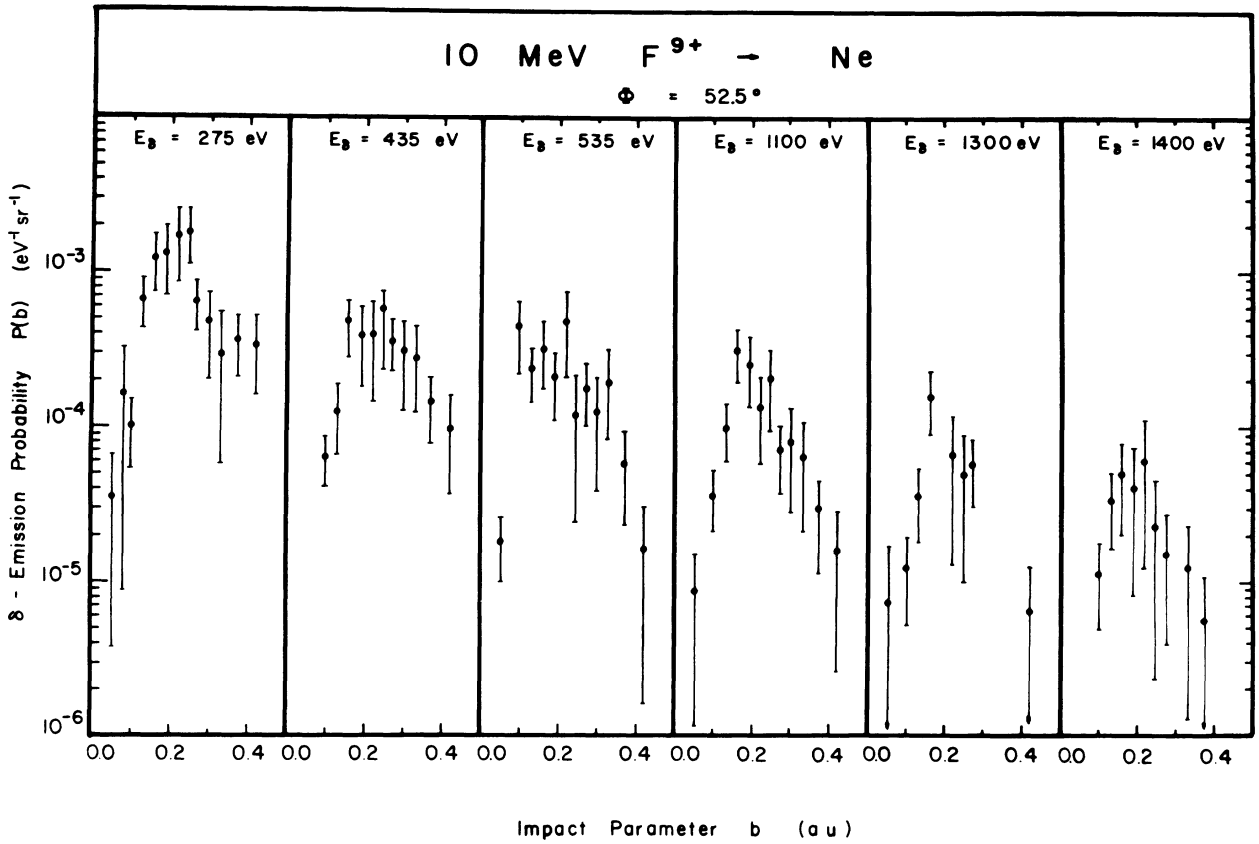

FIG. 4. Same as in Fig. 2, but for bare fluorine projectiles and $\Phi = 52.5° \pm 7.5°$.

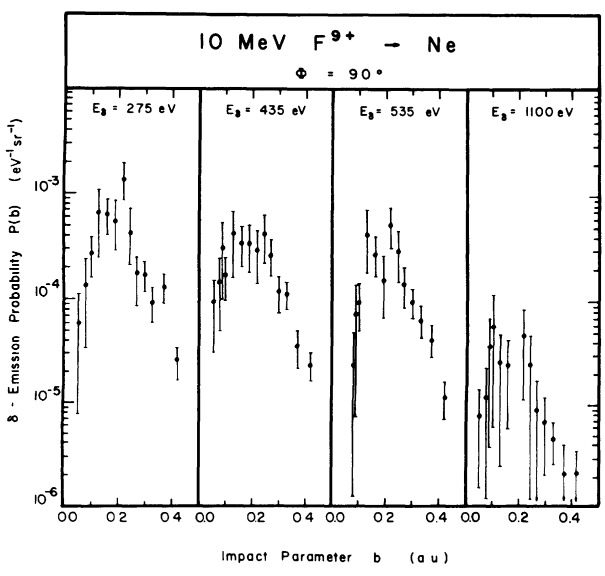

FIG. 5. Same as in Fig. 4, but for $\Phi = 90° \pm 21°$.

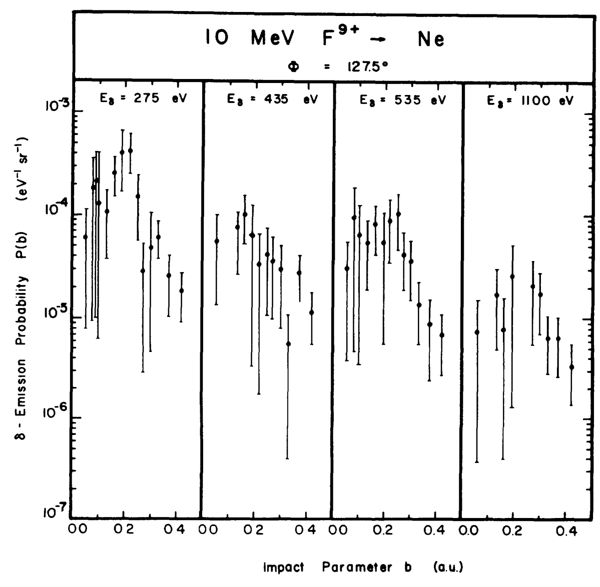

FIG. 6. Same as in Fig. 4, but for $\Phi = 127.5° \pm 7.5°$.

impact parameter b. The impact-parameter dependence of the δ-electron emission probability for all investigated systems is presented in Figs. 2–6. Several features can be readily observed.

Independent of the δ-electron energy E_δ, the δ-electron emission angle Φ, and the charge state of the incoming projectile, the δ-electron emission probability rises sharply with increasing impact parameter to a maximum value and then falls off somewhat exponentially. The maximum value of the emission probabilities is located at about 0.15 ± 0.02 a.u. and seems (within experimental errors) to shift slightly to smaller impact parameters for decreasing δ-electron energy. This region of maximum emission probability coincides with the adiabatic radius for *K*-shell electrons of neon for these collision systems, i.e., $r_{ad}(K)=0.146$ a.u., but does not seem to scale with a mean impact parameter estimated by using the Massey criterion on the basis of strong variations in screening as a function of δ-electron energy.[21,22] However, the sharp rise to this maximum for increasing impact parameters cannot, at the present time, be attributed to screening effects. Experiments to clarify this feature are desirable and in the process to be undertaken. In the cases where the effects of projectiles with different charge states on the δ-electron emission probability have been investigated, i.e., 10 MeV F^{q+} + Ne, $q=6$, 8, 9, $\Phi=90°$, it was found that the emission probability does not increase with the number of electrons brought into the collision. The values for $P(b,E_\delta,\Phi)$ obtained in collisions involving F^{6+} and F^{8+} as projectiles lie about 10 to 15% and 5 to 10%, respectively, below those obtained from collisions of F^{9+} with neon, which can be understood as due to screening effects by the projectile electrons.[21,22] This confirms results obtained by Cocke *et al.*,[11] namely, that target electrons are

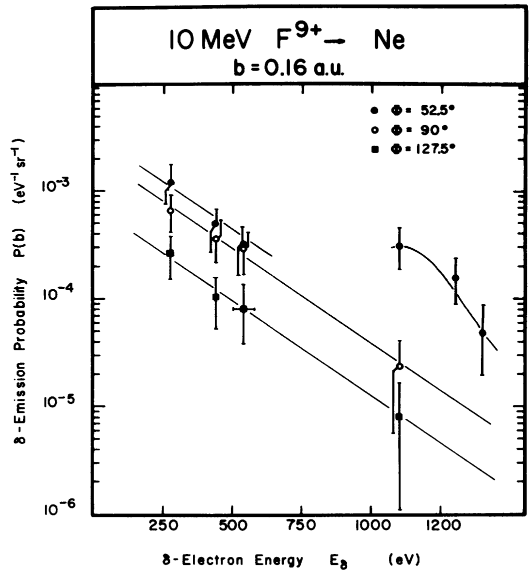

FIG. 7. Energy dependence for the neon δ-electron emission probability at $b=0.16$ a.u. for bare fluorine projectiles at 10 MeV for $\Phi=52.5°\pm7.5°$, $90°\pm21°$, and $127.5°\pm7.5°$. For uncertainties see Fig. 2.

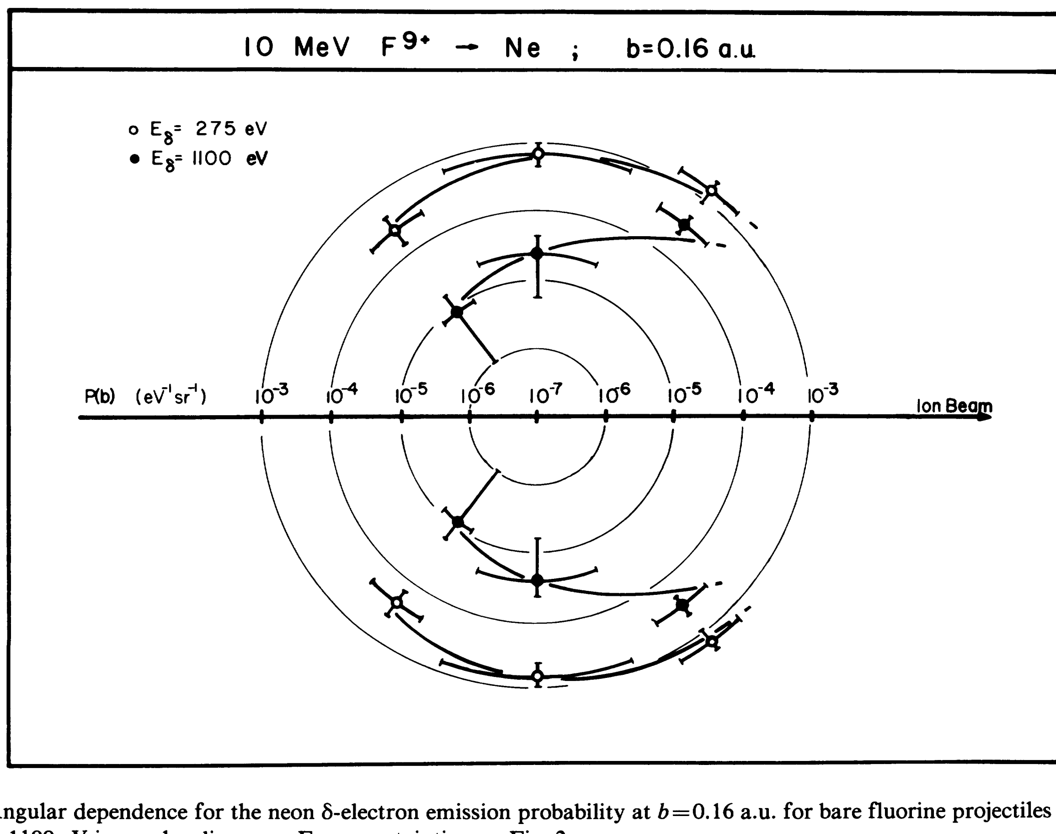

FIG. 8. Angular dependence for the neon δ-electron emission probability at $b=0.16$ a.u. for bare fluorine projectiles at 10 MeV for $E_\delta=275$ and 1100 eV in a polar diagram. For uncertainties see Fig. 2.

the major contributors to the δ electrons emitted at 90°.

(b) δ-electron emission probabilities as functions of the δ-electron energy E_δ. For δ-electron emission angles $\Phi=90°$ and 127.5°, the emission probabilities $P(b,E_\delta,\Phi)$ fall off exponentially with increasing δ-electron energy E_δ for all observed collision systems and all impact parameters (a typical example is shown in Fig. 7). This shape has its origin in the momentum distribution of the target electrons and is explained by Weigold,[23] McCarthy and Weigold,[24] Garcia,[25] and by Rudd.[26] Incidentally, the shape of $P(b,E_\delta,\Phi)$ vs E_δ of our experiment coincides with the one given by Rudd within 20%, however, the applicability of Rudd's arguments (i.e., slow collision, MO picture) to the neon L-shell electrons in this collision system has to be questioned.

For the system 10-MeV F^{9+} + Ne, $\Phi=52.5°$, the emission probability as a function of the δ-electron energy E_δ falls off exponentially with approximately the same slope as in the previous cases for δ-electron energies smaller than 600 eV. Above this energy the binary-encounter peak starts to play a major role (Fig. 7). Within the statistical errors this peak seems to become shallower and less wide for increasing impact parameters, indicating that the "hardness" of the collision with maximum momentum transfer to the electron decreases.

(c) δ-electron emission probabilities as functions of the δ-electron emission angle Φ. The angular dependence of the δ-electron emission probability was investigated in the system 10-MeV F^{9+} + Ne, $\Phi=52.5°$, 90°, and 127.5° with respect to the beam direction.

In Fig. 7 the emission probability as a function of E_δ is given for all three emission angles at $b=0.16$ a.u. The probability at $\Phi=127.5°$ is a factor 3 lower than at 90°. For $E_\delta<600$ eV, the probability at $\Phi=52.5°$ is a factor 1.5 above the one at 90°. Above this energy the binary-encounter peak is the major contributor to $P(b,E_\delta,\Phi)$ for $\Phi=52.5°$. If the same set of data is viewed in a polar diagram (Fig. 8), the strong asymmetric distribution of the emitted δ electrons in the beam-forward direction becomes obvious.

B. Theoretical considerations

In general three theoretical models describe the direct-Coulomb ionization by swift, point-chargelike projectiles. They are the plane-wave Born approximation (PWBA),[27-30] the binary-encounter approximation (BEA),[31-35] and the semiclassical approximation (SCA).[36-44]

While the SCA is based on an impact-parameter formulism by treating the trajectory of the projectile in a classical way and the projectile-target electron interaction quantum mechanically, the other two models in their original structure obtain cross-sections differential in electron energy and emission angle only. Based on the framework of the BEA, McGuire and Richard[34] obtained an extended model describing the ionization probability as a function of the impact parameter for ground-state hydrogenic target electrons and formulated appropriate scaling laws.

However, for the present collision system 10-MeV F^{q+} + Ne, neither sudden limit arguments of the above

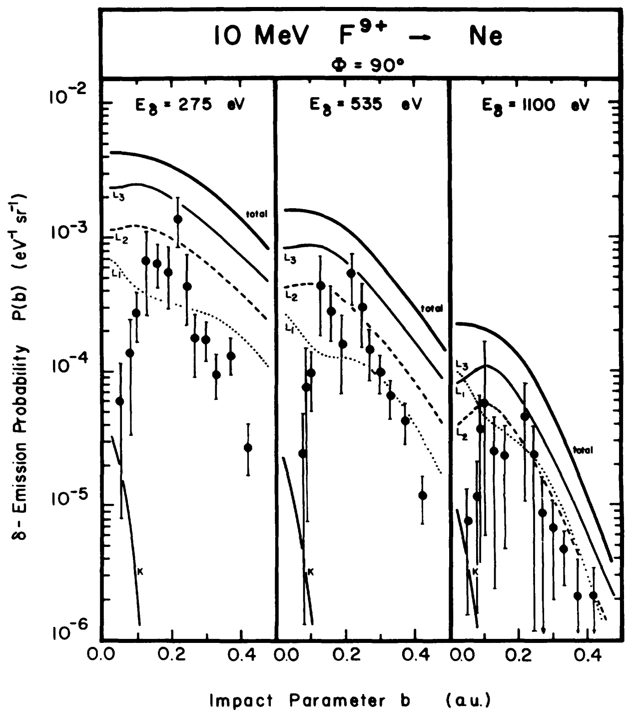

FIG. 9. Impact-parameter dependence of the neon δ-electron emission probability at $\Phi=90°\pm21°$ for bare fluorine projectiles at 10 MeV, compared to a theoretical SCA calculation (Ref. 46). For experimental uncertainties, see Fig. 2. The theoretical values are given for electron emission from the K shell, all L shells, and the total neon atom, and are subject to an uncertainty of 20%.

models, nor adiabatic limit arguments of the MO-model are entirely valid. Numerous additional assumptions and correcting terms have been applied to extend the BEA, PWBA, and SCA into the region of this experiment,[44] among them are corrections for the distortion of the classical Coulomb trajectory, recoil and binding effects, and for united-atom effects.[45]

The only available set of theoretical values to be compared to the experimentally obtained data of the present work is an SCA-type calculation performed by Trautmann.[46] δ-electron emission probabilities as a function of the impact parameter b, the δ-electron energy E_δ, and the δ-electron emission angle Φ have been calculated for the K shell and all L subshells of neon for impinging 10-MeV F^{9+} with $\Phi=90°$ by using relativistic hydrogenic wave functions, hyperbolic trajectories, and binding and recoil corrections. The theoretical values are subject to an uncertainty of 20% and are compared to the experimental data in Figs. 9 and 10. Large discrepancies exist in the magnitude and the impact-parameter dependence of the δ-electron emission probabilities. The steep drop for decreasing impact parameters b smaller than 0.15 a.u. especially is not predicted by theory (Fig. 9). However, the energy dependence of the emission probabilities is reproduced within experimental errors (Fig. 10). The incorporation of united-atom corrections, which causes the K- and L-shell electron emission probability for the

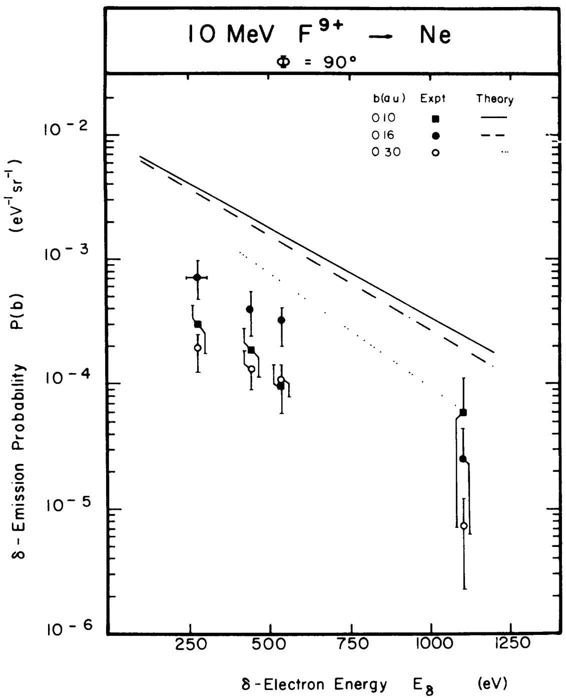

FIG. 10. Energy dependence for the neon δ-electron emission probability at $\Phi = 90^\circ \pm 21^\circ$ for bare fluorine projectiles at 10 MeV for $b = 0.10$, 0.16, and 0.30 a.u., compared to a theoretical SCA calculation (Ref. 46). For uncertainties see Fig. 9.

present collision system to be lowered by a factor of 2 to 4,[46] and the use of Hartree-Fock wave functions might reduce the discrepancies between experimental and theoretical values. Such calculations will be available in the near future.[46]

IV. CONCLUSION

The absolute triple-differential probabilities for the emission of δ electrons in 10-MeV F^{q+} + Ne, for $q = 6$, 8, and 9, have been measured as a function of the impact parameter, the δ-electron energy and the δ-electron emission angle. The probabilities show a strong asymmetry in forward beam direction due to electron originating in hard collisions with maximum momentum transfer to the electron (binary-encounter peak). For lower δ-electron energies the energy dependence takes an approximately exponentially decaying shape due to the momentum distribution of the target electrons. The impact-parameter dependence of the emission probabilities shows a strong peak at an impact parameter of about 1.5 times the *K*-shell radius (0.38 times the *L*-shell radius) of neon. A steep rise to this maximum, previously observed by Cocke *et al.*,[11] was also found in this collision system. On the average about five δ electrons are emitted per collision.

Further experiments to clarify the direct ionization process in ion-atom collisions are necessary. Among them are coincidence measurements between δ electrons and charge-state analyzed recoil ions, or δ electrons, scattered particles, and recoil ions. The not-well-understood steep rise of $P(b, E_\delta, \Phi)$ to its maximum for increasing impact parameters might be due to a dominant capture process of the neon *L*-shell electrons by the projectile. An experiment measuring the charge state and scattering angle of the projectiles coincident with δ and Auger electrons could clarify this process.

A comparison with a theoretical calculation based on the framework of the SCA reproduces the energy dependence of the δ-electron emission probability, but shows large discrepancies in the impact-parameter dependence and in the magnitude of the probabilities. The constant position of the maximum of $P(b, E_\delta, \Phi)$ vs b in all investigated collision systems is not understood. Further improvements of theoretical models, especially their extension into the region of this experimental collision system where neither adiabatic nor sudden limit arguments are valid, are highly desirable.

ACKNOWLEDGMENTS

We would like to thank C. L. Cocke and P. Richard for many helpful discussions, H. Schmidt-Böcking, and R. Schuch for making available the use of the PPAD and its supporting electronics, and D. Trautmann for carrying out the calculations in the semiclassical approximation. This work was supported by the U.S. Department of Energy, Division of Chemical Sciences.

[1]L. H. Toburen, Phys. Rev. A 9, 2505 (1974).
[2]Y.-K. Kim, Radiat. Res. 64, 96 (1975).
[3]M. E. Rudd, Radiat. Res. 64, 153 (1975).
[4]Y.-K. Kim, Radiat. Res. 64, 205 (1975).
[5]M. E. Rudd, L. H. Toburen, and N. Stolterfoht, At. Data Nucl. Data Tables 18, 413 (1976).
[6]T. L. Criswell, L. H. Toburen, and M. E. Rudd, Phys. Rev. A 16, 508 (1977).
[7]L. H. Toburen, S. T. Manson, and Y.-K. Kim, Phys. Rev. A 17, 148 (1978).
[8]S. T. Manson and L. H. Toburen, Phys. Rev. Lett. 46, 529 (1981).
[9]F. Bell, G. Trollmann, H. Böckl, and H.-D. Betz, J. Phys. B 15, 1487 (1982).
[10]Th. Weiter and R. Schuch, Z. Phys. A 305, 91 (1982).
[11]C. L. Cocke, H. Schmidt-Böcking, and R. Schuch, J. Phys. B 15, 651 (1982).
[12]J. H. Miller, L. H. Toburen, and S. T. Manson, Phys. Rev. A 27, 1337 (1983).
[13]L. Sarkadi, J. Bossler, R. Hippler, and H. O. Lutz, J. Phys. B 16, 71 (1983).
[14]C. Woods, R. Kauffman, K. Jamison, N. Stolterfoht, and P. Richard, J. Phys. B 8, L61 (1975).
[15]S. Hagmann, C. L. Cocke, J. R. Macdonald, P. Richard, H. Schmidt-Böcking, and R. Schuch, Phys. Rev. A 25, 1918 (1982).
[16]S. Hagmann, C. L. Cocke, P. Richard, H. Schmidt-Böcking, and R. Schuch, in Proceedings of the Third Winter School on

Energetic Atomic Collisions, Schönau, West Germany, 1982 (unpublished).
[17]S. Hagmann, C. L. Cocke, P. Richard, A. Skutlartz, H. Schmidt-Böcking, and R. Schuch, in *X-Ray and Atomic Inner-Shell Physics—1982,* proceedings of the International Conference on X-ray and Atomic Inner-Shell Physics, Eugene, Oregon, edited by B. Crasemann (AIP, New York, 1982).
[18]G. Gaukler, H. Schmidt-Böcking, R. Schuch, R. Schulé, H. J. Specht, and I. Tserruya, Nucl. Instrum. Methods 141, 115 (1977).
[19]M. Stöckli, Kansas State University (private communication).
[20]P. Dahl, M. Rødbro, B. Fastrup, and M. E. Rudd, J. Phys. B 9, 1567 (1976).
[21]J. H. McGuire, N. Stolterfoht, and P. R. Simony, Phys. Rev. A 24, 97 (1981).
[22]L. H. Toburen, N. Stolterfoht, P. Ziem, and D. Schneider, Phys. Rev. A 24, 1741 (1981).
[23]E. Weigold, Aust. J. Phys. 35, 571 (1982).
[24]I. E. McCarthy and E. Weigold, Am. J. Phys. 51, 152 (1983).
[25]J. D. Garcia, Phys. Rev. 177, 223 (1969).
[26]M. E. Rudd, Phys. Rev. A 20, 787 (1979).
[27]E. Merzbacher and H. W. Lewis, in *Handbuch der Physik,* Band XXXIV, edited by S. Flügge (Springer, Berlin, 1958), p. 166.
[28]G. S. Khandelwal, B. H. Choi, and E. Merzbacher, At. Data 1, 103 (1969).
[29]B. H. Choi, E. Merzbacher and G. S. Khandelwal, At. Data 5, 291 (1973).
[30]G. Basbas, W. Brandt, and R. Laubert, Phys. Rev. A 7, 983 (1973).
[31]M. Gryziński, Phys. Rev. 138, A305 (1965); 138, A322 (1965); 138, A336 (1965).
[32]J. D. Garcia, R. J. Fortner, and T. M. Kavanagh, Rev. Mod. Phys. 45, 111 (1973).
[33]J. S. Hansen, Phys. Rev. A 8, 822 (1973).
[34]J. H. McGuire and P. Richard, Phys. Rev. A 8, 1374 (1973).
[35]J. H. McGuire, Phys. Rev. A 9, 286 (1974).
[36]J. Bang and J. M. Hansteen, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 31, No. 13 (1959).
[37]J. M. Hansteen, O. M. Johnsen, and L. Kocbach, At. Data Nucl. Data Tables 15, 305 (1975).
[38]J. M. Hansteen, Adv. At. Mol. Phys. 11, 299 (1975).
[39]O. Aashamar and L. Kocbach, Z. Phys. A 279, 237 (1976).
[40]L. Kocbach, Z. Phys. A 279, 233 (1976).
[41]L. Kocbach, J. Phys. B 9, 2269 (1976).
[42]P. A. Amundsen, J. Phys. B 9, 971 (1976).
[43]P. A. Amundsen, J. Phys. B 10, 1097 (1977).
[44]D. Trautmann and F. Rösel, Nucl. Instrum. Methods 169, 259 (1980).
[45]J. S. Briggs, J. Phys. B 8, L485 (1975).
[46]D. Trautmann, Universität Basel, Switzerland (private communication).